CHAPTER VI

RELATIONSHIPS BETWEEN CROP TEMPERATURE, GRAIN YIELD, EVAPOTRANSPIRATION AND PHENOLOGICAL DEVELOPMENT IN TWO HYBRIDS OF MOISTURE STRESSED SORGHUM

B. R. Gardner, B. L. Blad, D. G. Watts and D. P. Garrity

ABSTRACT

Recent studies have shown that the grain yields of corn (*Zea mays* L.) and wheat (*Triticum aestivum* L.) are related to the degree of water stress experienced. The purpose of the study reported here was to establish predictive relationships between crop temperature and the grain yields, phenological development, evapotranspiration rates and leaf water potential values in two hybrids of grain sorghum (*Sorghum bicolor* L. Moench) that were subjected to varying levels of plant water stress.

The study was conducted at the University of Nebraska Sandhills Agricultural Laboratory in 1978. The sorghum hybrids used in this study were RS 626 and NB 505. Four irrigation treatments were applied in order to develop varying levels of water stress during each of three major growth stages. Soil moisture was monitored with a neutron probe. Crop temperature was measured with an IR thermometer and leaf water potential was measured with a Scholander pressure bomb.

Maximum grain yields were achieved with an irrigation treatment in which 80% of the water lost by evapotranspiration was replaced. Grain yields were reduced if water stress occurred during any growth period. Yield reductions were most severe

when stress occurred only during the grainfill period and least severe when stress occurred during the entire growing season.

The percentage reduction in sorghum grain yield was found to be well described by an index involving the seasonal accumulation of the daily temperature differences between well-watered and stressed crops (ΣTSD). The response curves had similiar slopes but different intercepts because of differences in the yield potential of the hybrids.

As ΣTSD values increased, ET decreased. However, the correlation of ET vs ΣTSD was relatively low ($R^2 = 0.60$), probably because of the relatively small amount of data available for analysis and inaccuracies in estimating ET using the soil water balance method.

We observed a temperature range of about 0.5 C between the well-watered rows in various plots for several days following an irrigation. However, in certain instances, the temperature range increased to 1-2 C for a few days before irrigation. This suggests that certain of the plots experienced water stress and should have been irrigated earlier. Yield data support that conclusion. Crop temperature appears to be a sensitive indicator of crop water stress in sorghum. If the temperature range in a uniformly treated sorghum plot exceeds about 0.5 C, the need for irrigation is indicated.

No significant difference occurred in the phenological development of sorghum as a function of water stress except in one NB 505 plot in which plants were stressed throughout the entire season. In that plot, the stressed plants lagged in development behind non-stressed plant by approximately ten days.

We examined the differences in mid-day leaf water potentials ($\Delta\psi_\ell$) and crop temperatures (ΔT) between stressed and non-stressed vegetation. As ΔT increased up to about 4 C, $\Delta\psi_\ell$ also increased. Beyond that point, $\Delta\psi_\ell$ decreased with further increase in ΔT. We attibute this behavior to stomatal closure which permitted an increase in ψ_ℓ of the stressed plants (hence reducing $\Delta\psi_\ell$) even as ΔT continued to increase.

INTRODUCTION

One particularly useful application of crop temperature data is in the detection of crop moisture stress. Temperature differences between stressed and non-stressed plants have been shown to be related to moisture stress (Palmer, 1965; Wiegand and Namken, 1966; Millar et al., 1971; Bartholic et al., 1972; Sumayao et al., 1977). Gardner and Blad (1980) and Idso et al. (1977) have provided quantitative data relating remotely sensed crop temperature to grain yields in moisture stressed corn (<u>Zea mays</u> L.) and wheat (<u>Triticum pestivum</u> L.), respectively.

It now appears that the prediction of crop yields and the assessment of economic impacts of drought can be improved by use of remotely-sensed crop temperature data. There remains a need for determination of crop temperature-plant water stress relationships for several agronomic crops. Additionally, the need exists for evaluations of varietal differences before remotely sensed crop temperature data can be used reliably.

The purpose of the study reported here was to determine the relationship between crop temperatures measured with an IR thermometer and the grain yields, phenological development,

evapotranspiration rate and leaf water potential in two hybrids of grain sorghum subjected to varying levels of soil water availability and, hence, of plant water stress.

MATERIALS AND METHODS

This study was conducted in 1978 in a 12-plot area located south of and immediately adjacent to the corn experiment described in Chapter II. The same irrigation system was used in both experiments. Sorghum was planted in 76 cm rows in 24 row plots. The rows were numbered from the line irrigation source. During a gradient treatment (G), row 1 was fully irrigated with decreasing application with distance from the line until, at row 22, no irrigation water was applied (Fig. 1). In a plot receiving any I treatment, all rows were fully irrigated.

The growing season was divided into three periods. The first period began when five leaves had fully emerged. It ended prior to the appearance of the panicle in the boot, i.e., at the time when spikelet differentiation was beginning. This corresponds to Vanderlip's (1972) Growth Stage 4. The second growth period included all other reproductive events, from the boot stage through the end of bloom. Growth period three extended from the end of bloom to physiological maturity. The phenological scale used in the study is summarized in Table 1.

Four irrigation treatments were imposed in this study: G-G-G, G-G-I, G-I-I and I-I-G. In the G-G-G treatment, a moisture stress gradient was maintained in the plot during the three growth periods. In the G-G-I treatment, a moisture gradient was maintained until the end of flowering. The soil profile was then

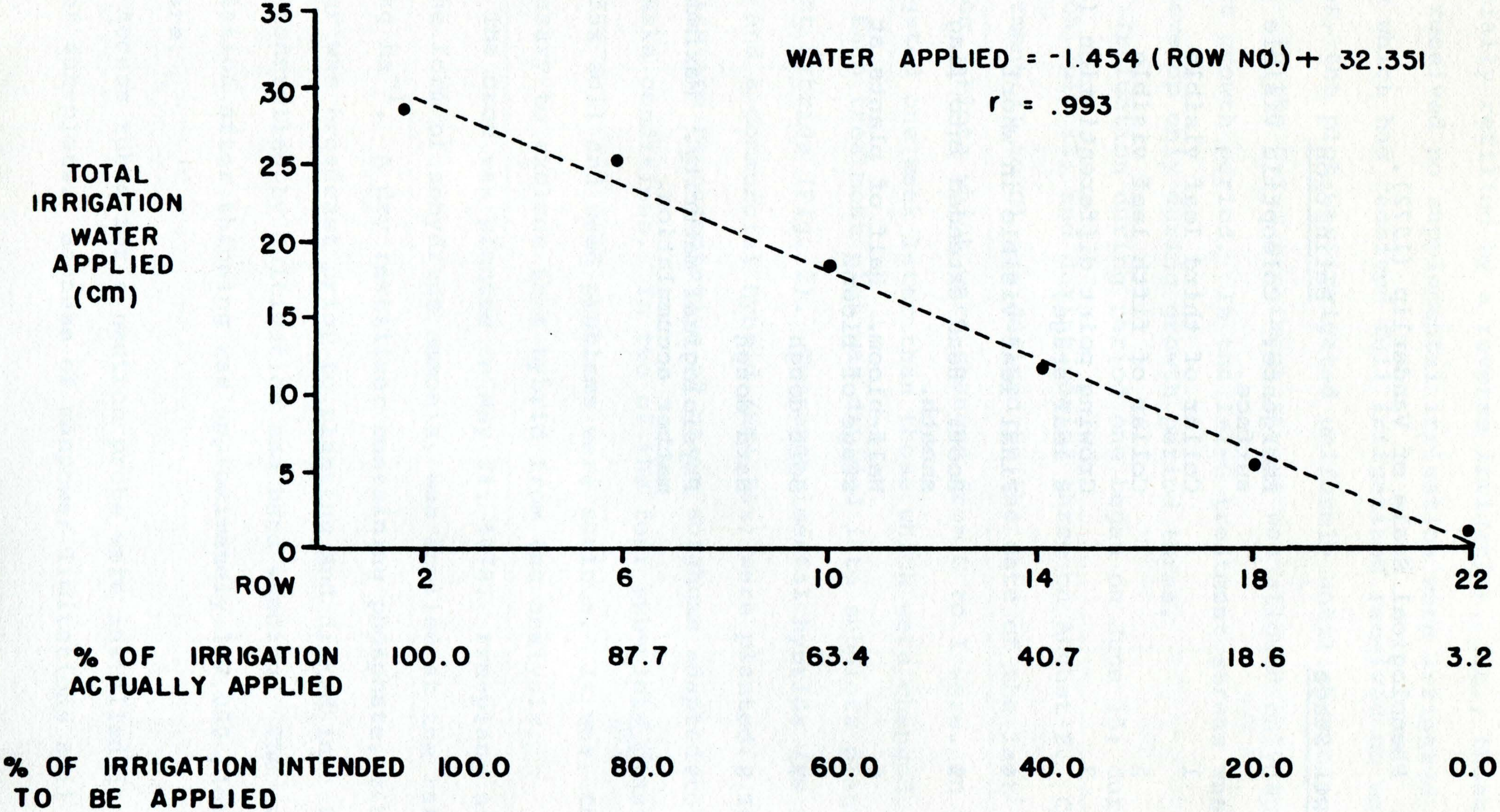

Fig. 1. Relationship between water applied and distance from the sprinkler line, and its correspondence to the percentage of ET replaced (adapted from Gilley et al., 1980).

Table 1. Phenological Scale of Vanderlip (1972).

Growth Stage	Definition
0	Emergence. Coleoptile visible at the surface.
1	Collar of third leaf visible
2	Collar of fifth leaf visible
3	Growing point differentiation (approx. 8 leaf stage)
4	Final leaf visible in whorl
5	Boot. Head extended into flag leaf sheath.
6	Half-bloom. Half of plants at some stage of bloom.
7	Soft dough
8	Hard dough
9	Physiological maturity. Maximum dry matter accumulation.

partially refilled by a reverse irrigation, i.e., those rows which had received no supplemental irrigation were irrigated and those rows which had received full irrigatiaon received no water. Thereafter, the plot was irrigated uniformly until physiological maturity. In the G-I-I treatment stress was allowed only during the first growth period. In the I-I-G treatment stress was allowed to develop only during growth period three.

Irrigation during period one began on June 15; during period two on July 15; and during period three on August 8. Changes in treatment (I to G) are defined by the date of the last full irrigation. Plots which were changed from G to I were, in each case, irrigated one week later than those which were changed from I to G.

Each treatment plot was divided into subplots planted to different hybrids (Fig. 2). Two experimental hybrids (RS 626 and NB 505) and a commercial hybrid (NC+ 55x) were planted. The three hybrids are representative of grain sorghums adapted to central Nebraska conditions. In two of the four sub-plots planted to NC+ 55x soil and weed problems were serious. It was, therefore, necessary to exclude that hybrid from the analysis.

The crop was planted on May 24, 1978. Pre-plant nitrogen in the form of anhydrous ammonia, was applied at the rate of 220 kg ha^{-1}. A dry fertilizer containing phosphate, zinc and sulfur was broadcast prior to planting and disked in. Weeds were controlled by cultivation and hand weeding. The average population after thinning was approximately 132,000 plants per hectare.

Access tubes for a neutron probe were installed in each set of sub-plots. Because of manpower limitations soil moisture

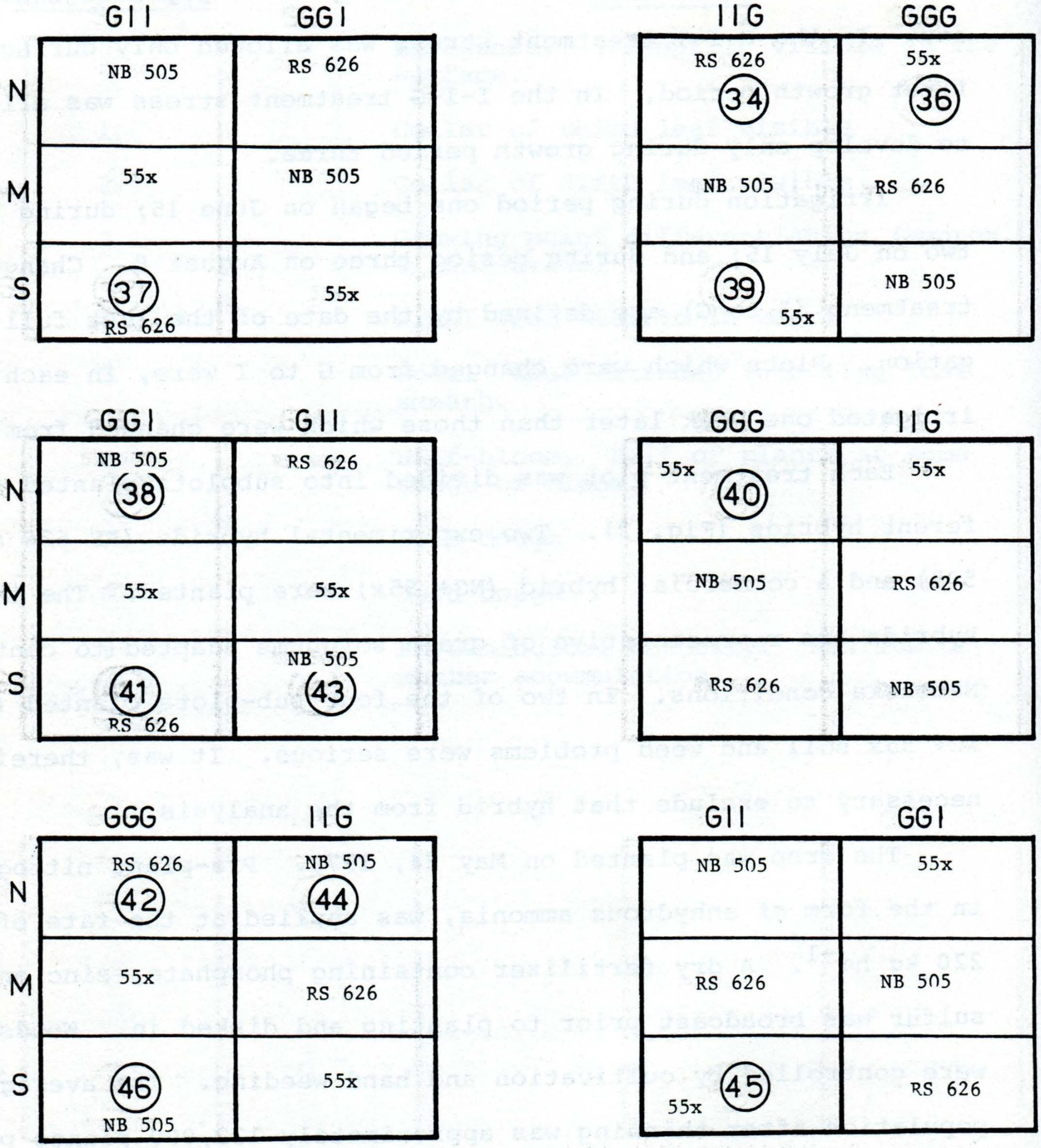

Fig. 2. Arrangement of sorghum plots used in 1978 study. Circled numbers indicate plots in which crop temperature was measured. Letters and numbers within each plot are the three sorghum hybrids. Letters above each plot indicate irrigation treatment.

was monitored in rows 14 through 22 in all plots but in rows 2 through 10 only in the middle sub-plot. Irrigations were scheduled weekly to restore water that had been depleted by evapotranspiration (ET) from the soil water profile in row 2.

Phenological observations were made at least weekly. Mid-day plant water potential measurements were made on selected clear days throughout the season in plot 42 with a Scholander pressure bomb.

Measurements were made daily throughout the growing season from atop a 12 foot ladder with a Barnes PRT 5 infrared thermometer on the selected subplots shown in Fig. 1. None of the IRT measurements were made in the middle subplots since distance from the ladder resulted in too large a spot size (2 x 6 m). In plots adjacent to the ladder, maximum width (E to W) of the observed spot was calculated to be 95 cm (approximately one row wide) and maximum length was 200 cm (N to S). In the subplots adjacent to the ladder spot-size was smaller than the yield sampling area. In the middle subplot, however, the spot-size was too great to be representative.

One crop temperature index (Index 1, Chapter IV) was tested in the estimation of crop growth stage. A temperature stress day index (TSD), defined as the mid-day crop temperature difference between the well-watered plants in row 2 and the plants in rows 6, 10, 14, 18 and 22 (Index 3, Chapter IV) was also used to estimate the reductions in yield and in ET caused by moisture stress. All IRT measurements were made using the procedures described in Chapter II.

RESULTS AND DISCUSSION

Effect of Irrigation Treatments on Evapotranspiration and Grain Yield

As expected, cumulative ET decreased as the ET replacement level decreased. The cumulative ET pattern on a G-G-G treatment for hybrid RS 626 is shown in Fig. 3. By the end of the first growth period, ET on the non-irrigated (zero % ET replacement) side of the gradient had fallen considerably below that for the non-stressed (100%) side. The gap between them continued to widen as the season progressed. Cumulative ET values for the other rows were found between these two extremes.

Maximum yields of the RS 626 hybrid for the G-G-G and G-G-I treatments occured in row 6, which received about 80% as much of the irrigation in row 2 (Fig. 4). In those cases grain yields at 80% ET replacement levels were about 800 kg ha^{-1} higher than with 100% ET replacement. For NB 505, any yield difference between 100% and 80% ET replacement levels was slight.

The less than maximal yield in the 100% ET replacement level treatment may have been due to an unfavorably humid microclimate favoring disease or insect incidence or by movement of fertilizer nutrients slightly deeper into a lower portion of the soil profile, making them less readily available to the plants. Because of the fine sand soil type, poor drainage due to overwatering is unlikely. Apparently, the adverse effects (whatever the cause) in the full irrigation environment become more pronounced as higher yield potentials are approached. Thus RS 626 was affected more adversely than was NB-505.

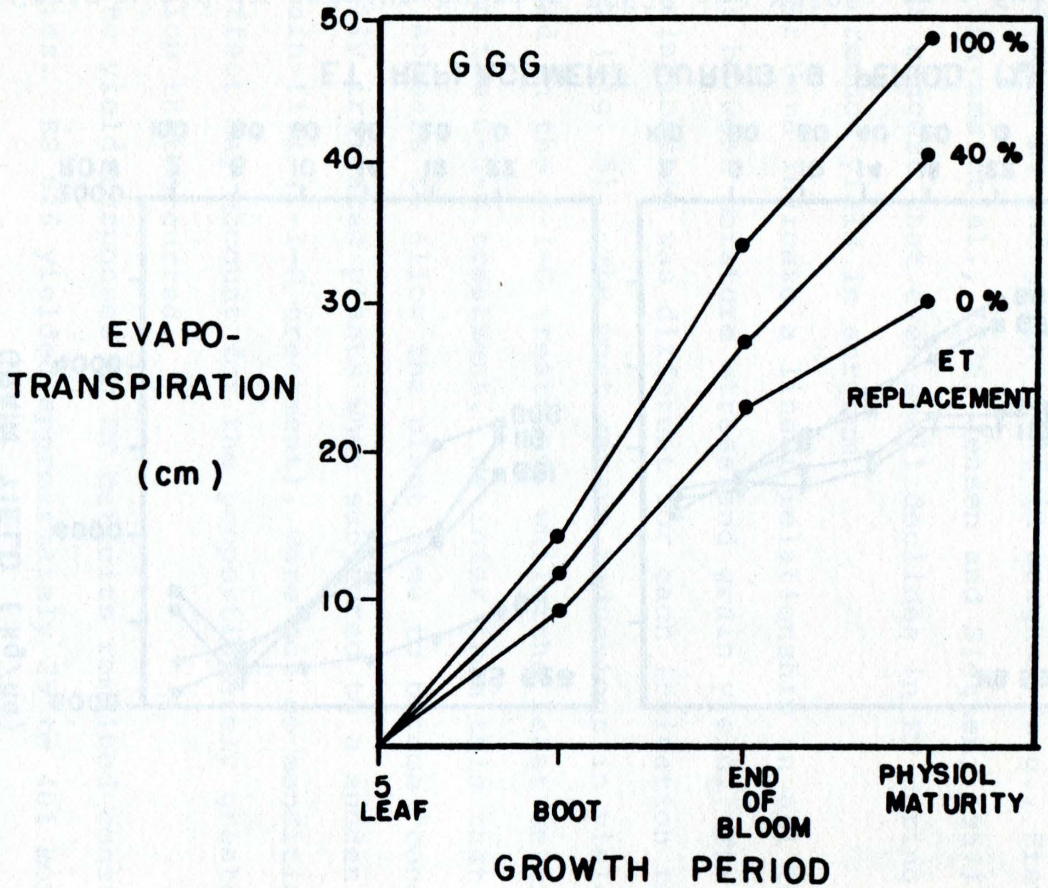

Fig. 3. The progress of grain sorghum evapotranspiration through the 1978 growing season compared among three ET replacement levels on the GGG treatment, hybrid RS626.

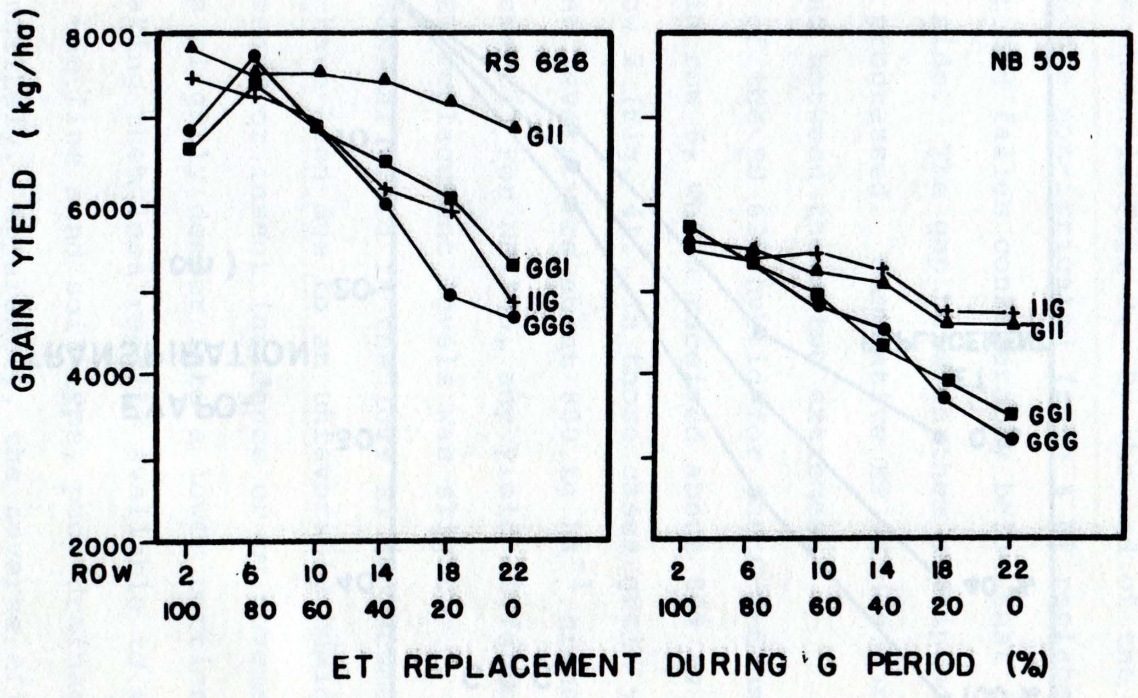

Fig. 4. Grain yield in sorghum hybrids RS626 and NB505, as a function of the percentage of ET replaced by irrigation for various irrigation treatments. Data are from the 1978 growing season at the Sandhills Agricultural Laboratory.

Early Season Stress Adaptation

The G-I-I treatment addressed the question of whether irrigation might be cut back during the vegetative and early reproductive growth stages without significant loss of grain yield. Castleberry (1973) showed that the leaf area and dry matter content of sorghum may be reduced to a considerable degree without affecting grain yields. Others have reported a linear relationship between ET and grain yield in sorghum (e.g., Stewart et al., 1974; Inuyama et al., 1976; Jensen and Sletten, 1957). These studies suggest that even small declines in ET during vegetative growth reduce yield in sorghum.

Our data indicate a linear relationship in all three growth periods between moisture stress and grain yield. The nature of this relationship was different for each irrigation treatment, however (Fig. 5). The most severe reductions in yield were observed in the I-I-G treatment, while the least severe reductions were in the G-G-G treatment. We infer from this that continuous stress appears to allow the plant time to become "conditioned." But fully irrigated plants when subjected to a sudden stress during grain-fill (I-I-G treatment), were not so conditioned and this effect may account for the proportionately greater yield reduction that occurred.

The yield responses to ET deficits remained constant between varieties. RS 626 yielded approximately 25 to 40% more than NB 505, regardless of irrigation treatment (Fig. 6). Nebraska dryland yield trial data for 1974-1978 support the conclusion that RS 626 consistently outyields NB 505 by an average of 25-30% over a wide range of environments. This may be due, in part, to the fact that

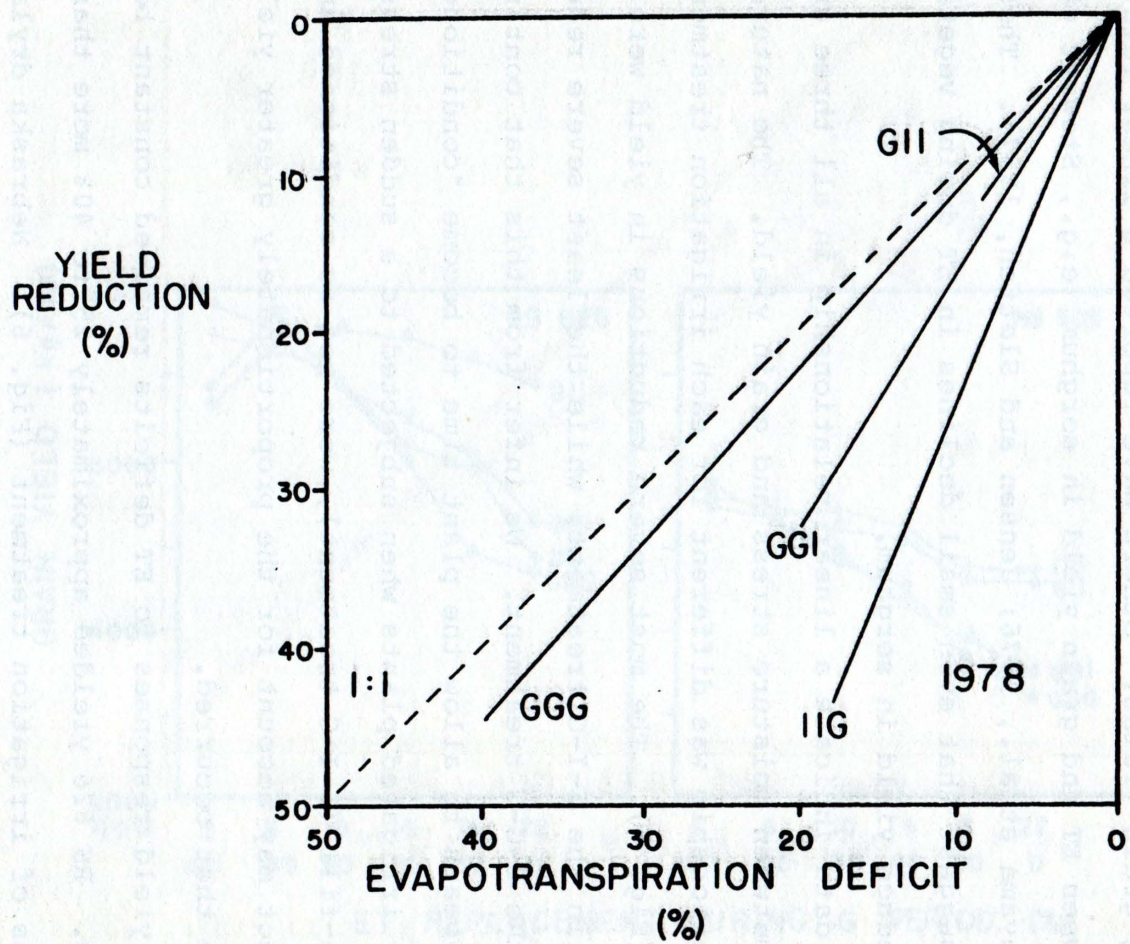

Fig. 5. Evapotranspiration deficits and yield reduction in hybrid RS626 for all gradient irrigations during 1978.

RS 626 requires about one week longer growing season than does NB 505 (Dreier, et al., 1979).

Another source of the variability in the yield relationship between these varieties may arise from differences in their rooting characteristics so that one variety may be a more efficient forager for water. Obviously, a method is needed to determine when differences in yield between varieties are due simply to environmental factors (availability of moisture in this case) or to genetic differences.

The crop yield data from this experiment are discussed in greater detail in Gilley et al. (1980) and Garrity (1980).

Relationship Between Crop Temperature and Grain Yield

The summation of the crop temperature differences between row 2 and other rows (ΣTSD) was examined for its relationship to grain yield in all irrigation treatments for NB 505 and RS 626 (Fig. 7). Although the two varieties yield differently the slopes of their response to ΣTSD are essentially the same. This finding has important implications for those who are attempting to assess the effects of drought on sorghum grain-yield reductions. If the yield potential in non-stressed conditions is known grain yield reductions might be estimated as a function of ΣTSD values.

One surprising result when crop temperature data are used as an index of stress is seen in a comparison of Figs. 5 and 7. Although the yield-ET relationship differs according to irrigation treatment, the yield-ΣTSD relationship appears to remain relatively constant between irrigation treatments. Thus, the large drop off in yield seen in the I-I-G treatment was associated with a large

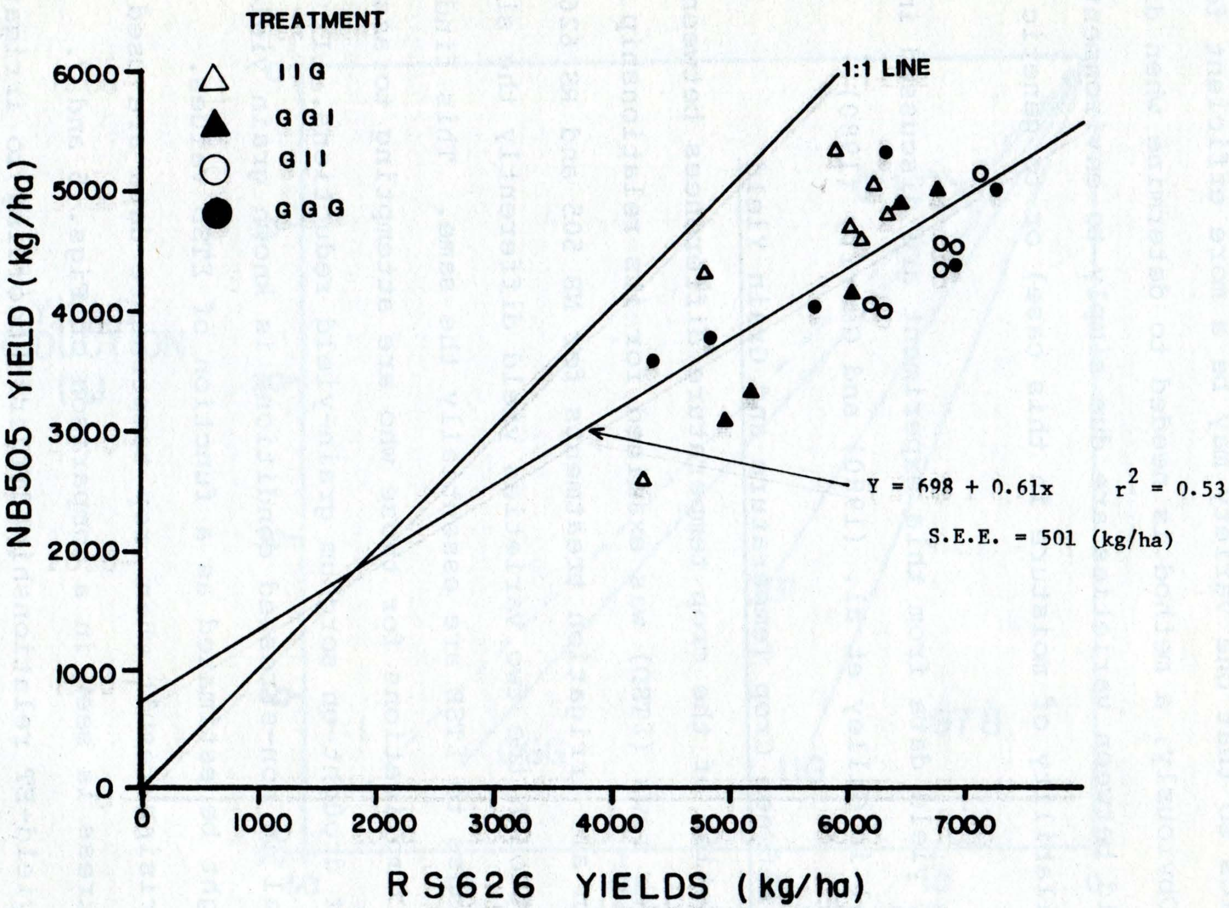

Fig. 6. Relationship between yields of RS626 and NB505 with similar irrigation treatments.

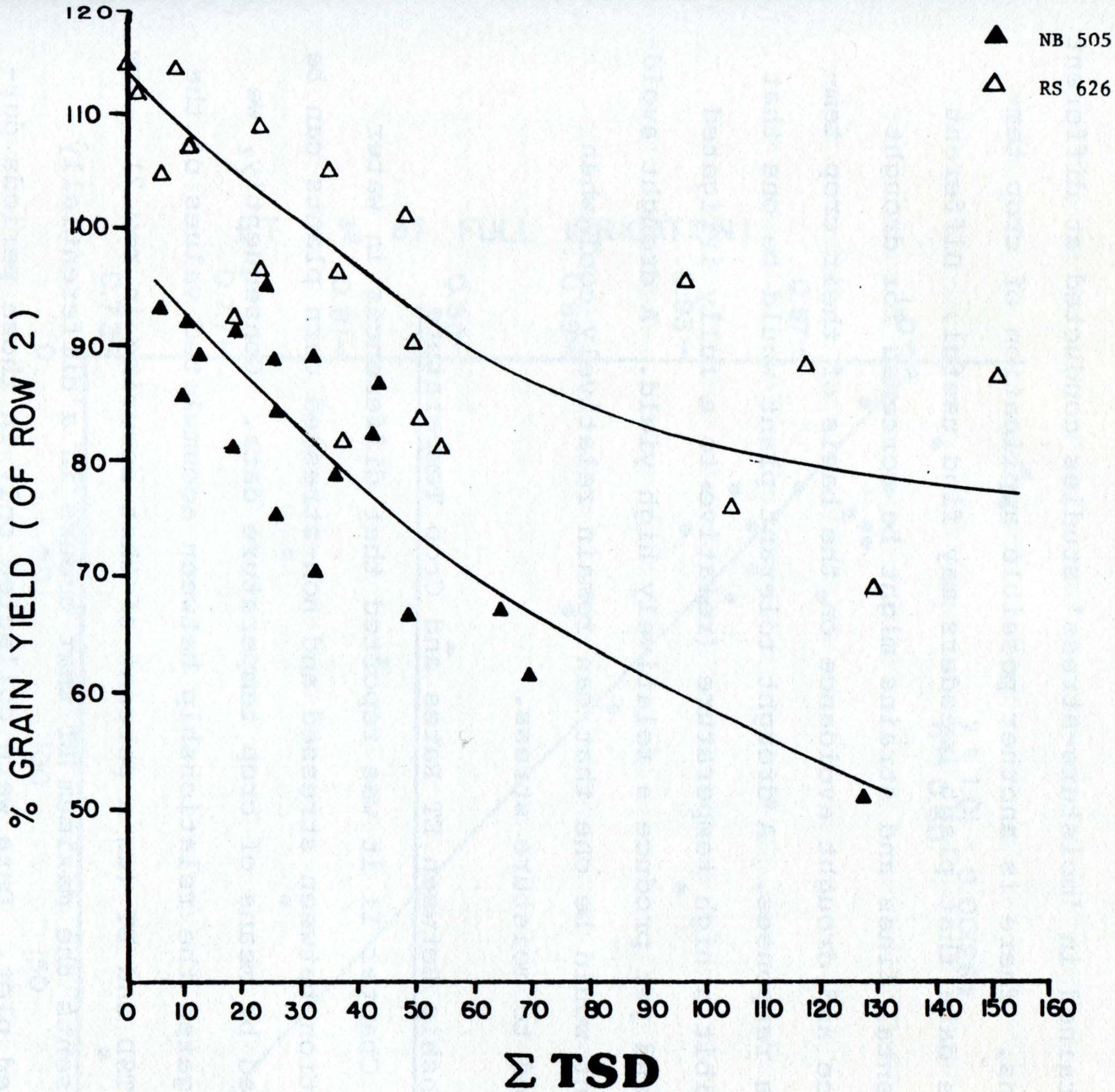

Fig. 7. Percent reduction in grain-yields as a function of ΣTSD for sorghum hybrids RS626 and NB505. Data were obtained in 1978.

increase in crop temperature of stressed plants during the G treatment.

Our results lead us to conclude that crop temperature measurements should provide an effective means for comparing yield data obtained in 'moisture-stress' studies conducted at different locations. There is another possible application of crop temperature data that plant breeders may find useful. Different experimental lines and strains might be screened for drought tolerance and drought avoidance on the basis of their crop temperature responses. A drought tolerant plant would be one that can exhibit a high temperature (relative to a fully irrigated plant) and yet produce a relatively high yield. A drought avoidant plant would be one that can remain relatively cool when subjected to moisture stress.

Relationship Between ET Rates and Crop Temperature

In Chapter II it was reported that differences in water consumption between stressed and non-stressed corn plants can be estimated by means of crop temperature data. Consequently, we investigated the relationship between accumulated values of the index ΣTSD and ET (as a percent of that occuring in row 2). Row 2 represents the maximum ET that occurs in a differentially irrigated plot. Data were collected only in those periods during which a plot was subjected to a "G" treatment.

The correlation between increased crop temperature and decreased ET was relatively low ($R^2 = 0.60$) (Fig. 8). One factor which may contribute to the variability of the data is the relatively small number of samples available for statistical analysis.

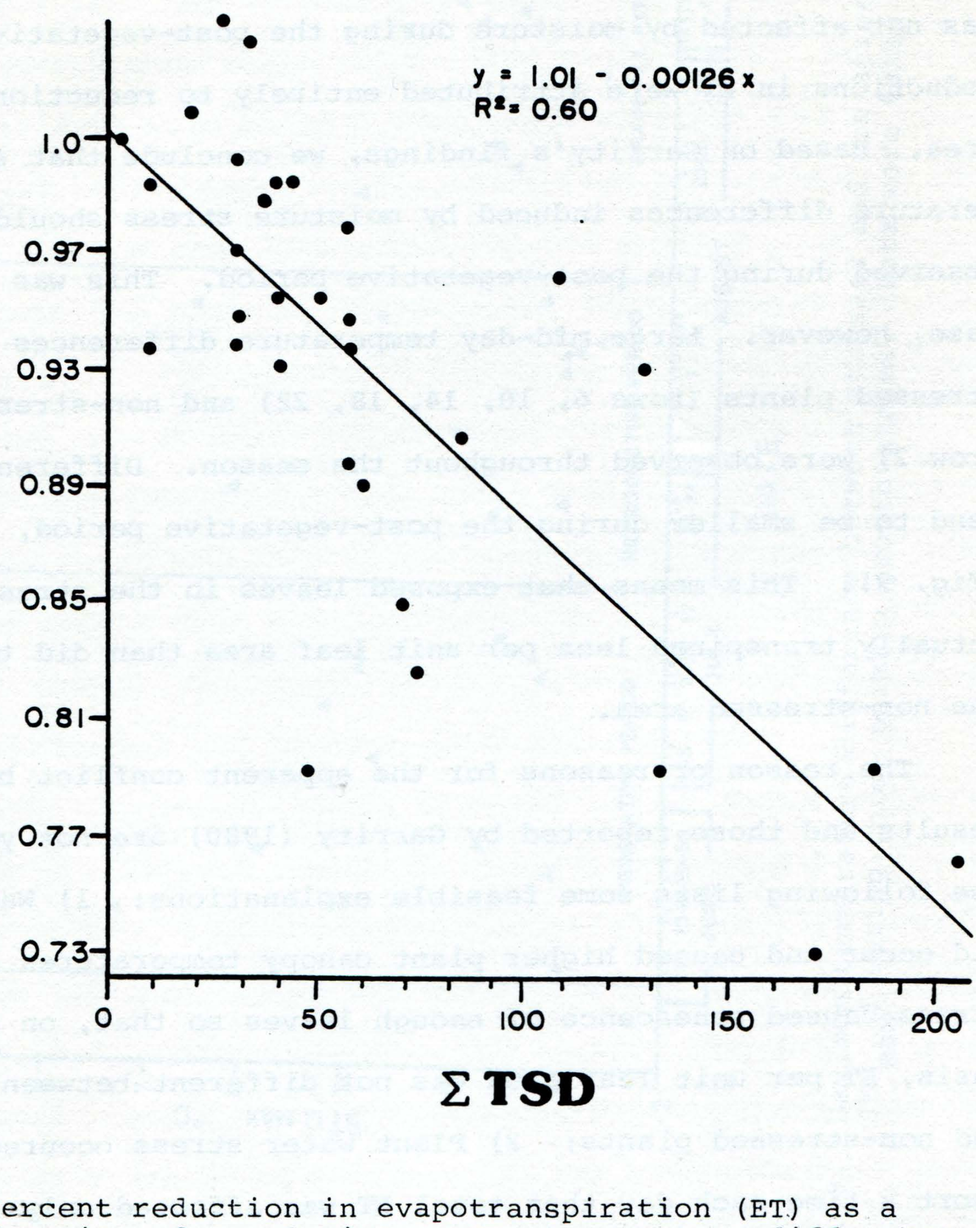

Fig. 8. Percent reduction in evapotranspiration (ET) as a function of cumulative canopy temperature difference (ΣTSD) between well-watered and stressed sorghum plants.

It is also likely that inaccuracies in estimating ET using the soil water balance method contribute to the variance.

Garrity (1980) found evidence that sorghum plants used in this study lost stomatal control after the vegetative period. He also reported that the average canopy (ET) per unit leaf area was not affected by moisture during the post-vegetative period. Reductions in ET were attributed entirely to reductions in leaf area. Based on Garrity's findings, we conclude that small temperature differences induced by moisture stress should have been observed during the post-vegetative period. This was not the case, however. Large mid-day temperature differences between stressed plants (rows 6, 10, 14, 18, 22) and non-stressed plants (row 2) were observed throughout the season. Differences did tend to be smaller during the post-vegetative period, however, (Fig. 9). This means that exposed leaves in the stressed areas actually transpired less per unit leaf area than did those in the non-stressed area.

The reason or reasons for the apparent conflict between our results and those reported by Garrity (1980) are not yet known. The following lists some feasible explanations: 1) Water stress did occur and caused higher plant canopy temperatures but the stress caused senescence of enough leaves so that, on a long term basis, ET per unit leaf area was not different between stressed and non-stressed plants; 2) Plant water stress occured during so short a time each day that total ET was affected only to a minor degree; 3) Because of reduction in the amount of leaf area in the stressed plots, the IRT may have viewed warm soil background thereby raising the apparent plant canopy temperature; 4) The

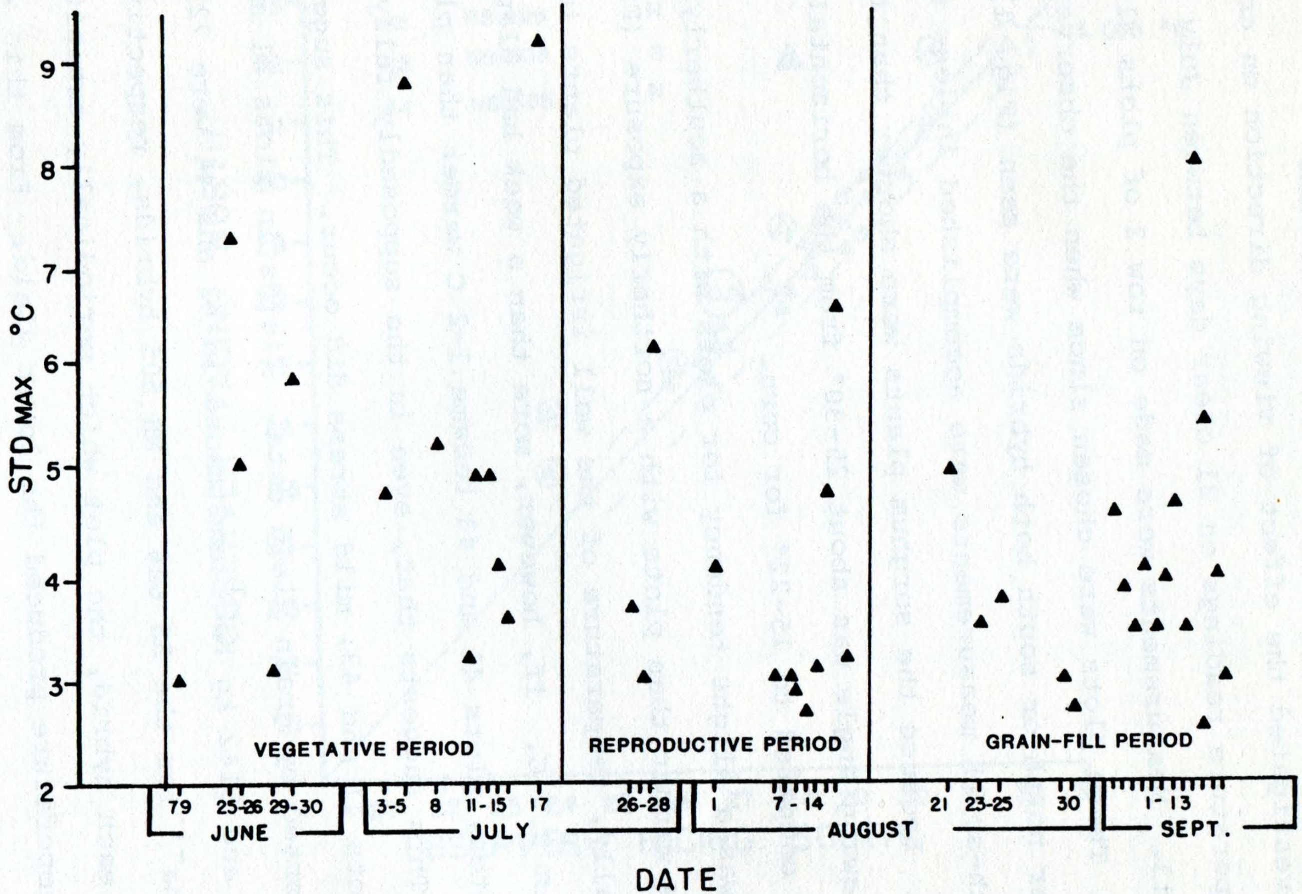

Fig. 9. Maximum temperature difference between stressed and non-stressed sorghum (STD_{max}) during three primary growth stages. Data were taken during 1978.

differences are due to measurement errors.

Application of Infrared Thermometry to Irrigation

We investigated the effect of viewing direction on crop canopy temperature readings on 21 clear days between July 24 and September 13. Measurements were made on row 2 of plots 41, 42, 43 and 44. These plots were chosen since when the observer faced either north or south both hybrids were seen (Fig. 1). A set of north-south measurements were accomplished in less than one minute. Because the sorghum plants were shorter than the corn the viewing angle was about 25-30° from the horizontal in the sorghum compared to 15-22° for corn.

There was a slight tendency for plots with a southerly exposure to be warmer than plots with a northerly exposure (Fig. 10). Generally, temperature of the well irrigated plants in row 2 were within 0.5 C. If, however, more than a week had elapsed since irrigaton, plots 41 and 43 became 1-2 C warmer than plots 42 and 44. This suggests that, even in the supposedly fully-irrigated plots 41 and 43, mild stress did occur. This suggestion is supported by grain yield data. Yields in plots 41 and 43 were 6733 and 5142 kg ha^{-1} and those in 42 and 44 were 7228 and 5388 kg ha^{-1} for the RS 626 and NB 505 hybrids, respectively. Thus, within each hybrid, the plot which periodically exhibited the warmer temperature produced the lower yield. From this we infer that sorghum yield is sensitive to moisture stress.

We conclude from these observations that crop temperature measurements provide a sensitive indicator of sorghum water stress and can be used to evaluate the efficiency of various irrigation

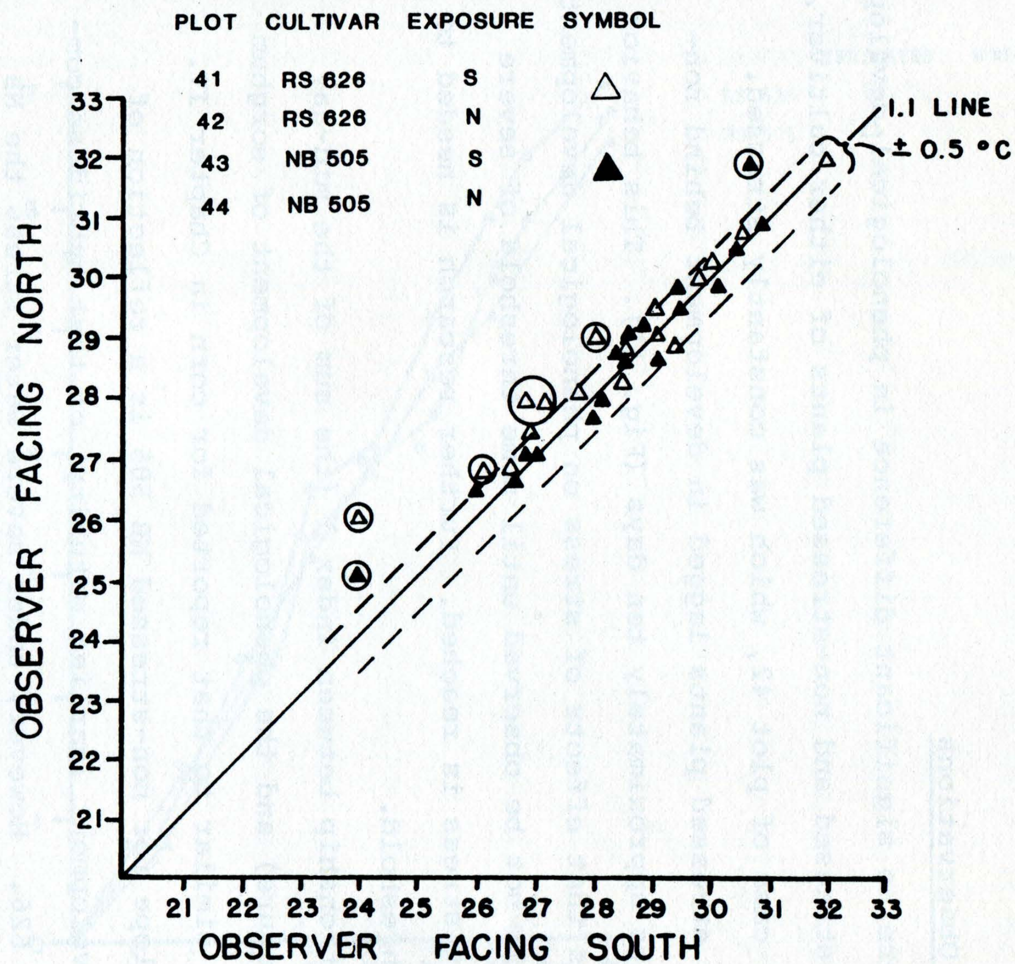

Fig. 10. Comparison of mid-day IRT temperatures of fully irrigated sorghum with the observer facing north and south on 21 clear days between July 24 and September 13, 1978, for two sorghum hybrids, RS626 and NB505.

scheduling techniques. Also on the basis of our results, it appears that if the crop temperature difference between two areas one of which is fully-irrigated, exceeds about 0.5 C, the need for irrigation of the warmer plot is indicated.

Phenological Observations

There were no significant difference in phenological development between stressed and non-stressed plants of either cultivar, except in the case of plot 42, which was constantly stressed. In this plot, stressed plants lagged in development behind non-stressed plants approximately ten days (Fig. 11). This behavior suggests to us that effects of stress on phenological development in sorghum will not be observed until some threshold of severe and persistent stress is reached. Further research is needed to define this threshold.

The relationship between index 1 (the sum of the mid-day canopy temperature) and the phenological development of sorghum (Fig. 12) was similar to that reported for corn in Chapter IV. The steeper slope for non-stressed NB 505 is a reflection of more rapid development (earlier maturity) of that hybrid as compared with RS 626. However, under severe water stress the NB 505 may be expected to mature later than would than non-stressed RS 626. These results provide further evidence that phenological development may be monitored by methods involving remote sensing.

Relationship Between Leaf Water Potential and Temperature Stress

The relationship between differences in mid-day leaf water potential ($\Delta\psi_\ell$) and difference in canopy temperature between stressed and non-stressed plants (ΔT) was studied on eleven clear

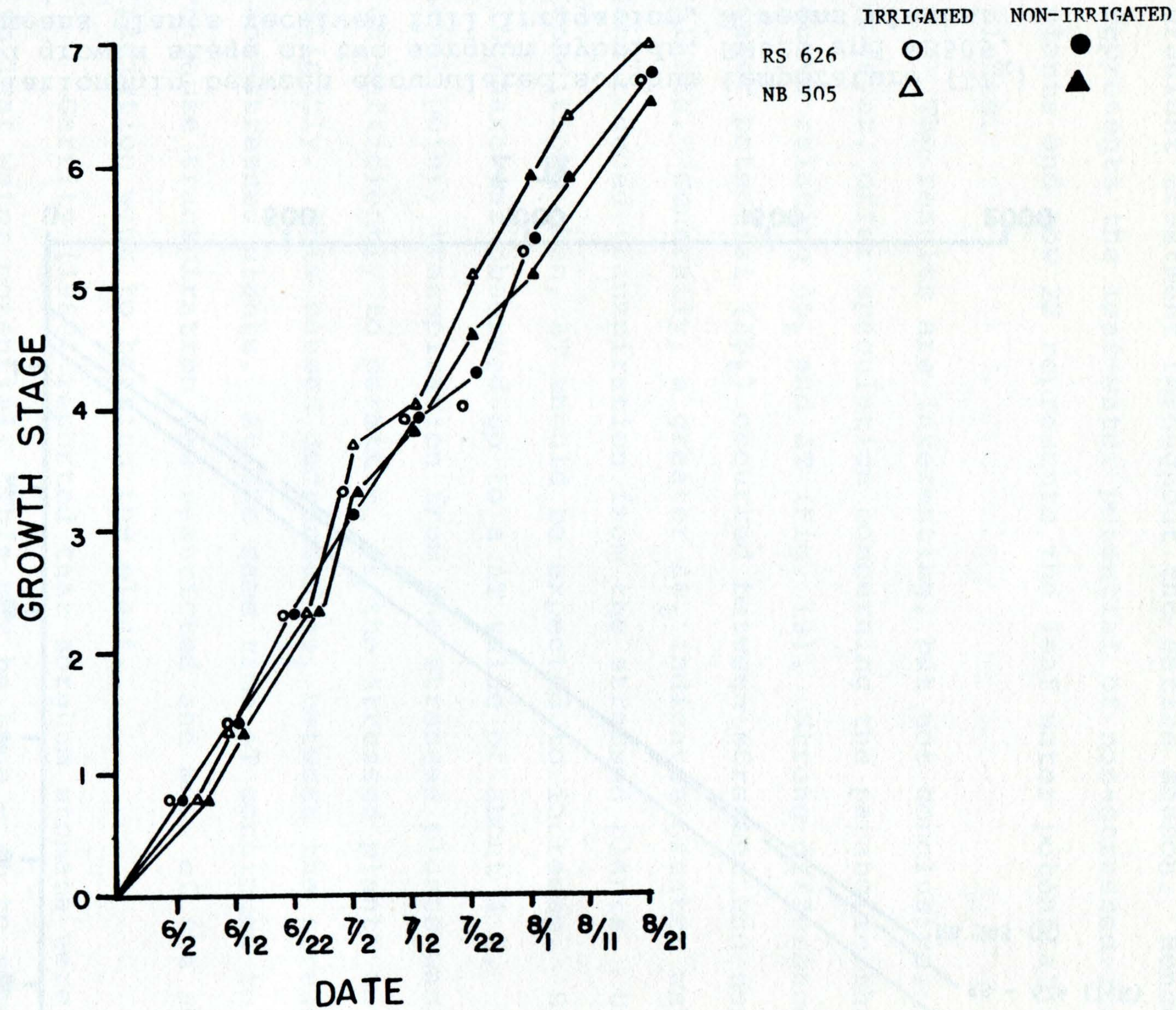

Fig. 11. Growth stages of two sorghum hybrids, RS626 and NB505, as influenced by water stress due to different irrigation treatment. Data obtained in 1978.

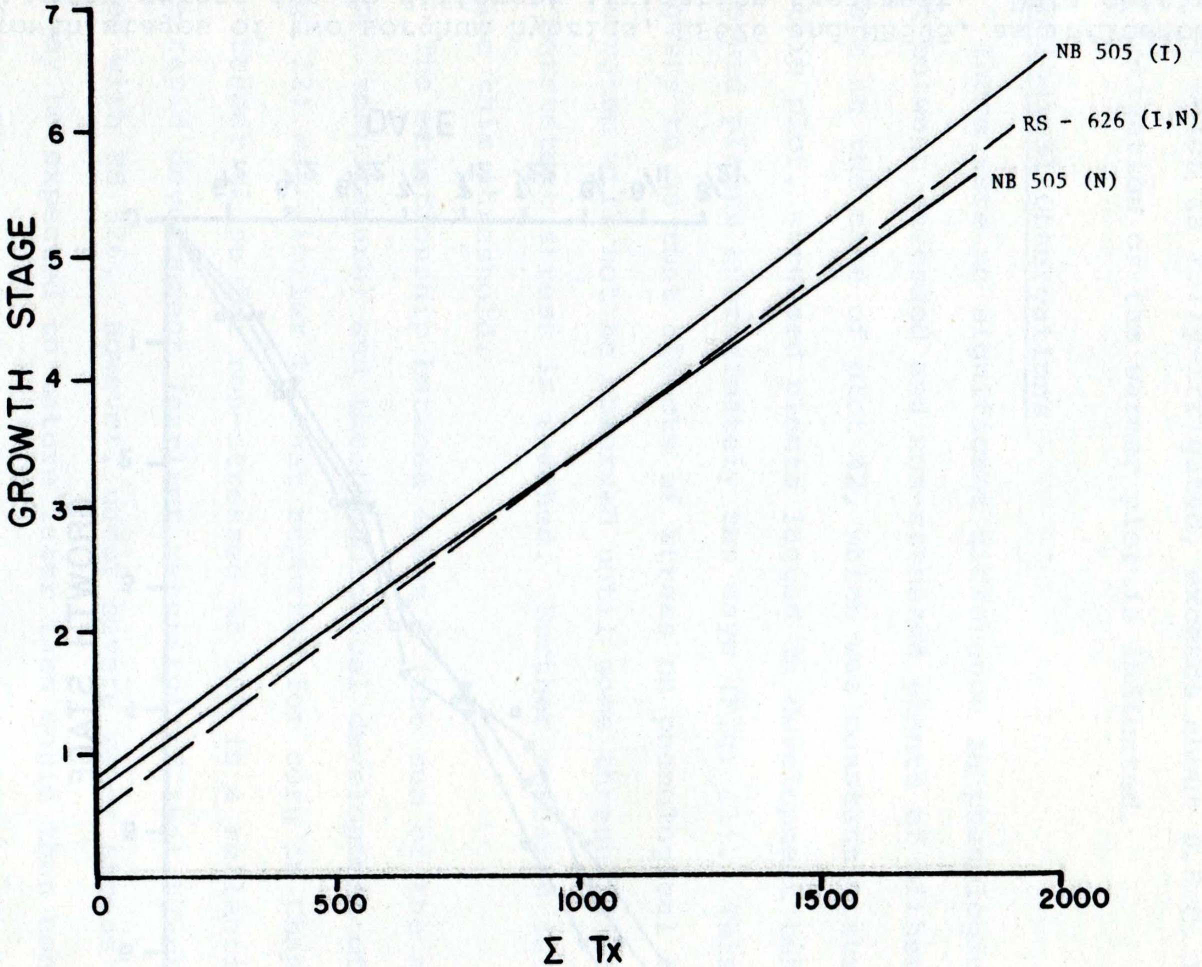

Fig. 12. Relationship between accumulated sorghum temperature (ΣT_x) and growth stage of two sorghum hybrids, RS626 and NB505. I means plants received full irrigation, N means plants received no irrigation. Data were obtained in 1978.

days between July 28 and September 4 (Fig. 13). Plot 42 was selected for this purpose since it was subjected to a moisture gradient treatment throughout the entire season. Hence, row 2 represents the leaf-water potential of non-stressed irrigated plants and row 22 represents the leaf water potential of dryland plants.

The results are interesting, but not conclusive. We can, however, offer speculation concerning the parabolic shape of the curve relating $\Delta\psi_\ell$ and ΔT (Fig. 13). Strong differences in leaf water potential ($\Delta\psi_\ell$) occurred between stressed and non-stressed plants. Generally, a greater $\Delta\psi_\ell$ indicates greater water stress and reduced transpiration from the stressed plants. Under such conditions then, ΔT should be expected to increase. Such an increase was observed up to a ΔT value of about 4 C. Beyond that point, transpiration from the stressed plants was restricted sufficiently to permit ψ_ℓ of the stressed plants to increase slightly. This caused decreased $\Delta\psi_\ell$ between the stressed and non-stressed plants. At the same time ΔT continued to increase because transpiration was restricted and more of the absorbed radiation went to heating the plant.

Garrity (1980) reported that sorghum stomata were insensitive to leaf water potential. This may be true - up to some critical level of stress. Once such a threshold is passed, however, stomates probably close. If stomates remain closed, whether by some chemical inhibitor or because of some other physiological effect, such mid-day ΔT values as we observe are possible. It may take from one to five days for the stomata to fully reopen once stress is removed (Hsiao, 1973). During this period of

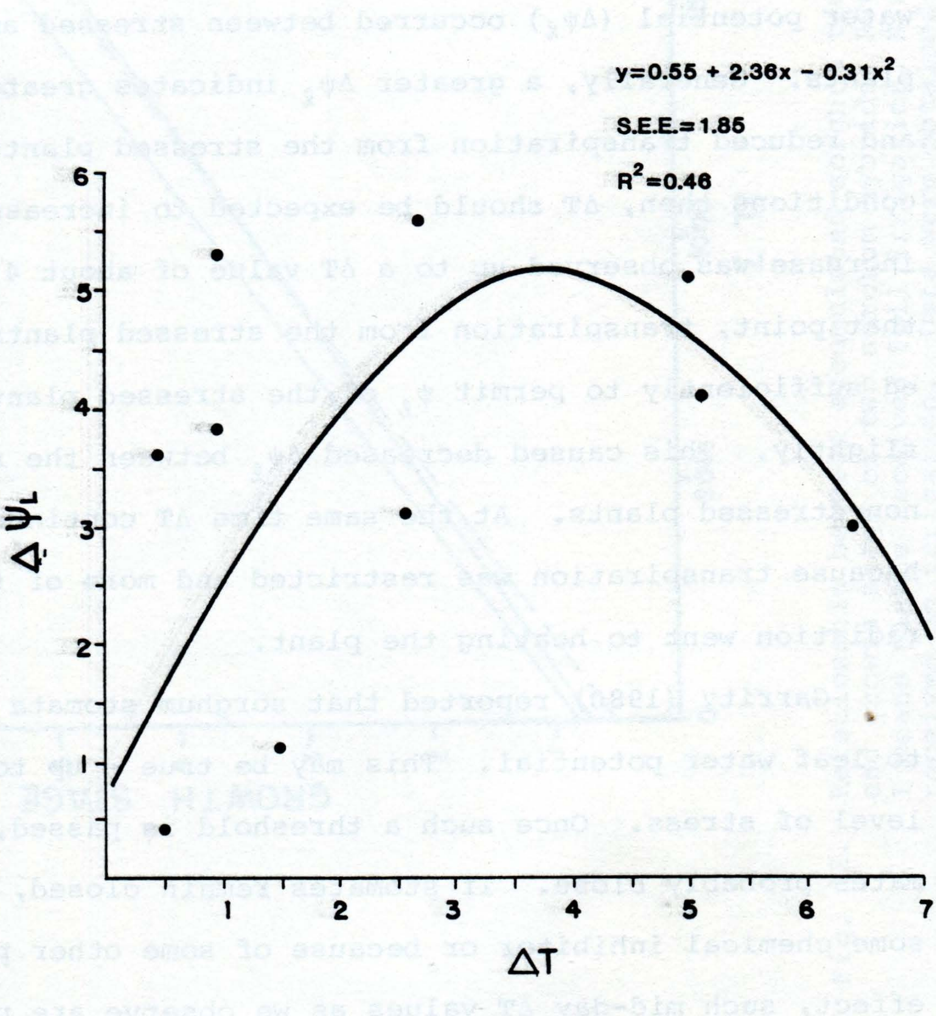

Fig. 13. Relationship between the difference in leaf water potential ($\Delta\psi_{\ell}$) and the difference in crop temperature (ΔT) between water-stressed and non-stressed sorghum hybrid RS626. Data obtained in 1973.

stomatal closure, $\Delta\psi_{\ell}$ would become smaller even though ΔT would continue to increase. The parabolic response shown in Fig. 13 is consistent with this suggestion. We expect to see this response only on severely stressed plants under high atmospheric demand situations.

Assuming that we are correct, an interesting problem arises in attempting to measure and evaluate stress on the basis of ψ_{ℓ} and crop temperature measurements. If $\Delta\psi_{\ell}$ is small, one might assume that actually stressed plants are non-stressed plants. But what if, at the same time, the stomata are closed? Then, ΔT will be positive in sign. More importantly, the stressed plant will not be photosynthesizing. Hence, the yield potential of the plant is reduced in spite of the lack of apparent water potential deficits. Thus, ΔT measurements may more accurately reflect the occurrence of plant stress than will $\Delta\psi_{\ell}$ measurements. More study is required, however, to establish the validity of the relationships between $\Delta\psi_{\ell}$ and ΔT that we observed. If the relationship can be established, research should follow to understand the mechanisms involved.

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